Auxiliary Power for Man in the Sea

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If men are to acquire the capability of performing useful work on the ocean floor, completely new techniques and equipment must be developed. The sources of power and the tools normally used in manual work on land are generally unadaptable to the underwater environment. The environment itself must be thoroughly understood. The adverse characteristics must be circumvented and the favorable characteristics must be capitalized upon in the design and use of equipment. This paper is intended to place in proper perspective the problems involved in working in an underwater environment and to point out potential methods of efficiently supplying the auxiliary power essential to the performance of this work.

ANY motion of man in the sea is opposed by a resistive force much greater than that encountered in air. Yet his net weight in water is close to zero, which results in an inability to resist the forces and torques involved in most forms of work. Thus his tools must be designed in such a way that minimum motion is required and a force and moment balance is obtained. Mechanical means of amplifying muscular actions must be based on a recognition of these factors in the output of work.

The relative efficiency of supplying auxiliary power from the surface or from sources on the bottom is an important concern. Surface units can take advantage of air breathing engines but have the disadvantage of requiring connections from the surface to the man on the bottom. They are also plagued with the effect of the surface motions of the ocean. Bottom power sources, on the other hand, must rely on either chemical or nuclear energy sources or power storage systems. The tradeoffs between surface-supplied power and bottom power sources are primarily a function of depth of operation, but other factors must also be taken into consideration.

Use can be made of the forces of gravity and buoyancy in developing auxiliary power for undersea work. The escaping air or gas used by the diver for breathing provides a continuous supply of buoyant force from which energy can be recaptured. With proper control of these forces they can be used for interchange of equipment between surface and bottom, and the available work can be put to good use in furnishing the auxiliary power necessary to aid the man on the bottom in the accomplishment of assigned tasks.

In any over-all operation that employs men working on the floor of the ocean, there are certain logistic requirements that place restraints on the effectiveness of the work performed. Generally there will necessarily be some form of surface vessel acting as a tender which hovers over the work area. This vessel must be in communication with the men on the bottom and will serve to replenish supplies, equipment, and personnel.

The surface vessel will be subjected to the forces of wind and sea. Either it must be allowed to move about in response to these forces or it must be designed for minimum motion when the forces are acting upon it. Translational motions may be resisted either by fitting the vessel with a maneuvering propulsion system or by anchoring it. The motions of roll, pitch, and heave can be minimized only by reducing the waterline area and transverse and longitudinal moments of inertia.

As a minimum requirement the surface vessel must have the capability of hovering within a small radius of a point directly above the men on the bottom. For the depths of water in which men are capable of working, an anchoring system is probably the most practical means of meeting this requirement.

Anchoring does little to restrict the motions of pitch, roll, and heave. And if the surface vessel is designed to minimize these motions it will lose the reserve buoyancy needed to support the anchor cables. Attempts to design minimum motion anchored surface vessels or buoys have usually resulted in a very complex and expensive mooring system. It, therefore, appears that for practical operations the rolling, pitching, and heaving motions of the surface vessel must be tolerated. Also from a practical standpoint, unless an extremely heavy anchoring system is used, there will be a fair amount of translational motion of the surface vessel with changing winds, seas, and currents.

These motions of the surface tender have a definite influence on the power supply for bottom operations. The motions dictate that the number of lines running to the men on the bottom be kept to an absolute minimum. Furthermore, the lines remaining must have sufficient strength and slack to prevent parting, and anchors must be provided on each to keep the lower ends within the work area.

The restriction on the use of lines from surface to bottom and the strength requirements imposed on them tends to reduce the feasibility of supplying power directly from the surface vessel for use by men on the bottom. However, other factors should be examined before discarding this possibility entirely.

There are three basic forms of power which can be transmitted by line from a surface vessel to the bottom. These are electric, hydraulic, and pneumatic. Each can be generated aboard ship with conventional auxiliary power equipment.

Electric power transfer is probably the most efficient of the three. It can be transmitted through conventional cables which can be supplied with the strength and flexibility required. Pneumatic hose provides the transfer of compressed air from surface to bottom. Here the transmission efficiency varies directly with the pressure used. However the stiffness of the hose also increases with pressure which tends to impose a limit on the efficiency which can be achieved. Hydraulic hose has similar limitations. In addition the hydraulic fluid cannot be exausted when used, and therefore an additional return line must be provided.

If power-transfer lines are used from surface to bottom, they would generally terminate in a distribution box or manifold. Individual lines would then be run from this central location to the equipment or tools using the power. For equipment that is fixed in one location on the bottom throughout an entire operation, this is equally feasible with all forms of power. However when equipment or tools must be moved from one location to another, it becomes somewhat more difficult.

Anyone familiar with the morass of air hoses, gas hoses, and welding cables around a ship under repair in a shipyard can

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picture the confusion that could exist on the ocean floor around a vessel being salvaged. Some of the heavier cables would sink into the bottom and some of the lighter hoses would form a tangled network of spaghetti which would constitute a distinct hazard to underwater swimmers. There would be more time spent in straightening out the power supply lines than working on the salvage job.

Unless each power tool were to have its own power line to the distribution box, it would be necessary to work with underwater connectors both at the tools and at the distribution box. With pneumatic tools and equipment this is quite feasible, since quick-disconnect connectors are readily available. These connectors can allow the escape of a short blast of air which clears the connector of seawater and prevents contamination of the compressed air. Similar connections are available for hydraulic lines, but the loss of hydraulic fluid and the danger of seawater contamination are somewhat greater problems.

Electric-power cable connectors have been developed for underwater use. However they are far from practical devices for routine underwater work. Any seawater that is not cleared when the connection is made is a potent source of electrolytic corrosion, and the possibility of power loss through short circuits is great. In addition the danger to underwater workers in using electrical equipment cannot be overemphasized. The possibility of electrocution because of stray currents or improper insulation is so great that electric power must be eliminated from consideration for use in hand-operated tools and equipment.

The general conclusions which can be drawn from the foregoing discussion are: 1) electric power use for an underwater operation should be restricted to a single power cable leading to a central location from the surface vessel, 2) the electric power should be used only for equipment that is fixed in this central location for the duration of the operation, and 3) all hand power tools and other equipment that is moved about the site should be driven by a nonelectric, portable source of stored auxiliary power.

The only practical auxiliary power source that meets this requirement is compressed air stored in portable tanks. This is a proven and reliable form of power which has been used for many years in the construction industries and which has many unique advantages for underwater work.

First it is of interest to evaluate the amount of power which is available when stored within a given size of container. In Fig. 1 is shown an idealized pressure-volume diagram which indicates how the amount of stored power is calculated.

Assume that all of the air in a tank is discharged through a device such as an air motor. From the tank pressure p_1 and volume v_1 the air will expand through the motor to the volume v_2 at the pressure p_2 and then will discharge into the surrounding water dropping to the ambient pressure p_3. The work

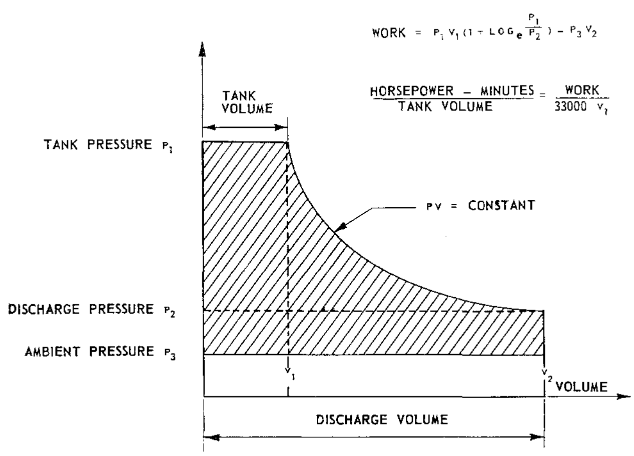

Fig. 1 Idealized pressure-volume diagram.

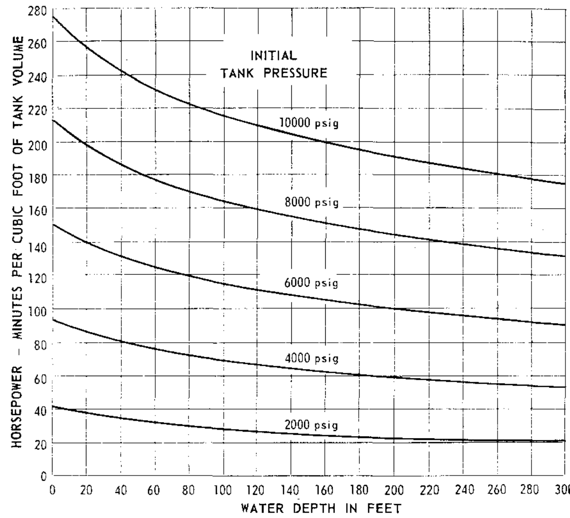

Fig. 2 Variation of stored power with tank pressure and ambient pressure at discharge.

done is represented by the shaded area and is given by the equation in the upper right of the figure. If the pressures are expressed in pounds per cubic foot and the volumes in cubic feet, the horsepower available can be expressed as the work divided by 33,000 t where t is the time in minutes over which this energy is used.

If it is assumed that the discharge pressure is twice the ambient pressure, the results can be expressed in terms of horsepower-minutes per cubic foot of tank volume. Figure 2 shows contours of this expression for various initial tank pressures and ambient pressures given in terms of water depth.

These curves indicate that it would be advantageous to use very high tank pressures since the power available in a 10,000-psi tank averages about eight times that in a 2000-psi tank. However there are other factors to be considered which ameliorate this apparent advantage.

Air compressors which are available for shipboard installation seldom have the capability of compressing air to the higher-pressures. In addition, the air tanks themselves must be of much heavier construction to withstand high pressures, high-pressure tools are difficult to design, and the danger to underwater workers increases with the tank pressure used. For these reasons it is probably feasible to consider only tank pressures in the range of 2000 to 3000 psi.

In order to illustrate power-storage capabilities, a simplified compressed air tank shape has been assumed which consists of a cylinder with two hemispherical ends. Cylinder diameter and total length of the tank have been varied. Wall thickness has been altered as a function of diameter and tank pressure to provide ample burst strength. Figure 3 shows curves of horsepower-minutes available for various tank diameters and lengths for a tank pressure of 2500 psi at a depth of 100 ft.

As a means of comparison with a more familiar power storage device, a 12-v automobile storage battery with a 40-amp-hr rating has an equivalent capacity of 38.6 hp-min. This is equal to the capacity of a 2500-psi air tank 8 in. in diameter and 3 ft, 6 in. long.

If air tanks are to be carried from place to place by underwater swimmers, their weight in water is an extremely important consideration. For the same series of tanks used in Fig. 3, the weight in water when filled with air at 2500 psi is shown in Fig. 4. It is fairly obvious that only the smallest of these tanks can be considered as portable.

Operational considerations of supplying charged tanks to the bottom from the surface vessel and sending empties back up to the surface require some control to be exercised over weight and buoyancy. It would be desirable to use tanks that would sink to the bottom at a slow rate when full of air and rise slowly to the surface when empty. With these

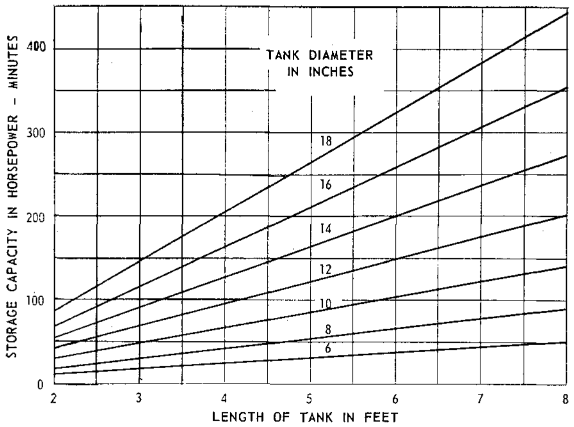

Fig. 3 Storage capacity of air tanks designed for initial pressure of 2500 psig discharging at 100-ft depth.

characteristics, the supply and return of tanks could be accomplished by having them ride a messenger line or anchor line between surface and bottom.

To achieve reasonable rates of falling and rising, the net weight in water should not exceed one or two pounds positive or negative. This can of course be attained by the addition and removal of weights or auxiliary buoyancy tanks. However it would be best to select tank sizes and pressures that require a minimum of additional fittings.

Figure 5 shows how the weight of 4-ft-long, air-filled tanks of different pressure ratings varies with power-storage capacity. It can be noted that only the 2000-psi tanks of this length fall within the suggested range of full weight in water without additional buoyancy being provided. For example, the weight range of 1 to 3 lb heavy occurs with 4-ft, 2000-psi tanks in the range of 12 to 14 in. in diameter. This gives power ratings of 75 to 100 hp-min.

The picture changes somewhat when empty weight in water is considered as shown in Fig. 6. The 2000-psi 4-ft tanks have net buoyancies ranging from 7 to 41 lb over the range of diameters shown. This is rather excessive and it appears that it would be desirable to go to higher-pressure tanks to obtain the desired buoyancy characteristics.

It is rather difficult to select a single tank that has a good combination of weight and buoyancy plus a large power-storage capacity. In fact it appears essential to provide either added buoyancy or weight to meet these criteria.

One tank of reasonable size and capacity would be a 2400-psi tank, 10 in. in diameter and 66 in. long. This tank would have a power-storage capacity of 91 hp-min at 100 ft. It would weigh 179 lb in air and would be 27 lb heavy in water when filled with air under pressure. When the air had been used it would have a net buoyancy of 3 lb.

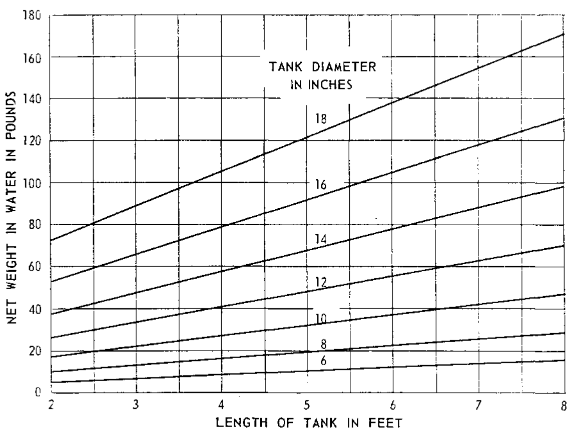

Fig. 4 Weight in water of tanks designed for an initial pressure of 2500 psig.

To this tank could be added a floodable ballast chamber of about 0.4 ft³ which would extend its length by about 9 in. This chamber could be blown out for lowering, giving a net weight in water of about 1.5 lb. As air was used by the underwater workman, water could be admitted to the ballast chamber to compensate for the loss in weight. Finally, when the internal air was used up the tank could be released and would rise to the surface at a reasonable rate.

There are, of course, several other sizes of tanks and tank pressures which would meet the requirements. However, for portable tanks it appears that on the order of $1\frac{1}{2}$ hp-hr is a reasonable power-storage capacity to expect at an operating depth of 100 ft. This capacity would be reduced to some extent at greater operating depths.

In the selection of air tanks to provide the stored power needed for underwater operations we have attempted to utilize to the best advantage the forces of weight and buoyancy. Similar considerations must be given in the design of tools to perform work underwater.

When working above water or on land, a man's weight is a primary factor in the design of both the hand tools and the power tools that he uses. For example, when drilling a hole either with brace and bit or with a hand electric drill, the worker either applies his weight directly for downward drilling or indirectly through the friction of his body against a solid surface in drilling a horizontal hole.

When working underwater this is not practical. To weigh him down sufficiently to apply the same forces that he can exert on the surface would make any other actions quite difficult. He could no longer swim from one point to another. Walking on the bottom is slow, arduous, and most of the time would stir up sufficient silt to reduce visibility. The underwater worker could be provided with a variable ballast system, but it appears more practical to build the compensation into his tools to meet the conditions of his environment.

There is an added force which must be overcome in the design of underwater tools and equipment. This is the resistance that develops with motion through the water. This force is proportional to the square of the velocity of motion and the cross-sectional area of the body being moved. Therefore it can be seen that velocity and area should be minimized in the performance of any item of work and in the design of any tool.

As an obvious example of these forces at work underwater, consider the simple action of driving a nail with a hammer. The normal action on land is to extend the length of the arm with a solid, light handle on the end of which is affixed a heavy piece of steel. The hammer is raised slowly by bending the arm at the elbow. It is then brought down at high velocity to

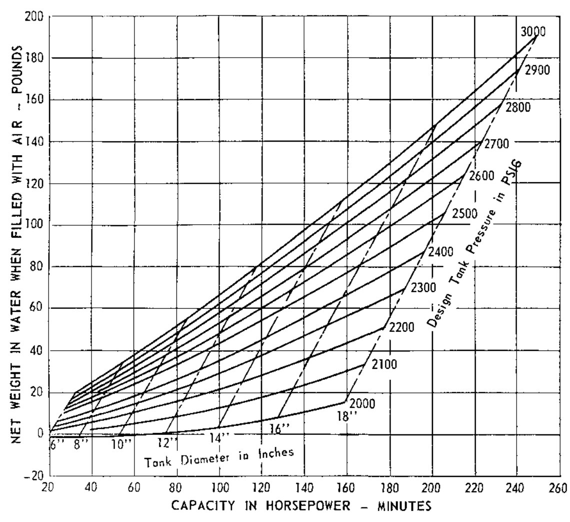

Fig. 5 Weight in water as a function of storage capacity of 48-in.-long tanks when filled with air.

mpact on the head of the nail. The twin reactions of the impact cause the nail to penetrate the material into which it is being driven and cause the head of the hammer to bounce back returning partially for the next stroke.

If it were attempted to execute the identical operation underwater, the raising of the hammer would be accomplished more slowly or a great deal more muscular effort would be required to raise it at the same speed. On the downstroke a man would be incapable of exerting the effort required to achieve the same velocity as in air with a standard one-pound hammer. In fact to attain the same impact energy with the same muscular effort on the downstroke the hammer would have to weigh on the order of 300 lb in air to overcome the forces of resistance and buoyancy. In addition, the reaction of the underwater worker on the downstroke would cause him to rise from his working position and he would have to return himself to position either by swimming or pulling himself back down using the hammer as an anchor.

This one simple example demonstrates that a tool designed for work in air is completely unsatisfactory for underwater work. In varying degrees this applies to all of the other basic tools such as wrenches, drills, screwdrivers, saws, files, and so forth. It applies to power tools as well as hand tools.

Although this discussion is primarily concerned with power equipment, it is worthwhile to continue briefly with a discussion of hand tools and then indicate how benefit can be gained from proper application of power assistance.

In designing a hammer for underwater work the principles involved in another hand tool, the staple gun, are adaptable. The staple gun is operated by squeezing together a pair of handles which in turn compress a spring. When the handles approach each other a pawl is retracted which releases the spring. This drives a bar down to impact on a staple and drives it into the material. If a cylindrical hammer head were substituted for the drive bar, this would make a fairly good underwater hammer.

The action of the operator in squeezing the handles together involves no reaction that would tend to change his position. There is, however, a reaction involved in the expansion of the spring, in the inertia of the moving hammer, and in the hammer head striking an object. To overcome this reaction the resistance of water to the motion of bodies through it can be employed to advantage.

Suppose a diaphragm were mounted on the top of the converted staple gun in such a way that its center would be pulled slowly down into the gun during the cocking part of the stroke. As the spring was released, and the hammer cylinder driven down, the center of the diaphragm could be driven upwards. The resistance of the surrounding water to the motion of the diaphragm would counteract the reaction to the spring expansion and to the impact. In this way the reaction forces could be completely balanced out throughout the cycle.

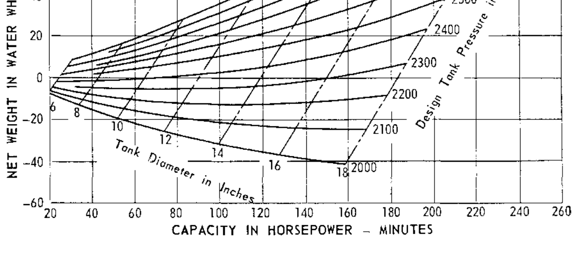

Fig. 6 Weight in water as a function of storage capacity of 48-in.-long tanks when empty.

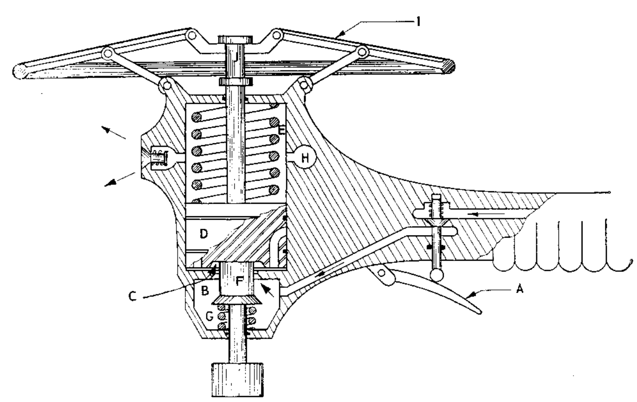

Fig. 7 Air-powered underwater hammer.

An adaptation of this general concept in the form of an air-powered hammer is illustrated in Fig. 7. The position shown is at the start of the hammering cycle.

When the operator presses the trigger A, air is admitted to the chamber B and passes into the cylinder C. The piston D is forced upward compressing the spring E. As the piston raises off the valve-hammer element F, the element rises due to the action of the spring G and shuts off air flow to the cylinder. The air within the cylinder continues to expand, raising the piston until it reaches the exhaust port H. When the air pressure is released, the spring E drives the piston down to impact against the valve-hammer element, which provides the driving force of the hammer and also opens the valve for the next cycle.

Reaction to the downstroke and impact is balanced by disk element I at the top of the hammer. During the upstroke of the piston, the stem J lowers the solid periphery of the disk. When the piston is driven downward this disk periphery moves rapidly upward. The resistance to this motion provides a downward force in opposition to the upward force generated by the piston travel and impact.

With proper design, an air hammer of this sort can be made to operate with minimum force reaction on the underwater worker. It can also provide efficient utilization of stored air power. Similar principles can be used in the design of air-powered impact wrenches to eliminate torque reaction on the operator.

In other torque applications such as an air-powered drill, it is necessary to apply an axial force as well as to balance out the torque reaction. Figure 8 illustrates a concept for employing the resistance of water to motion for this purpose.

A high-speed air motor is used to drive the worm A, which through the worm wheel B rotates the spider C of a differential gear assembly. The left-hand bevel gear D of the differential, through the attached spur gear E, drives spur gear F which is

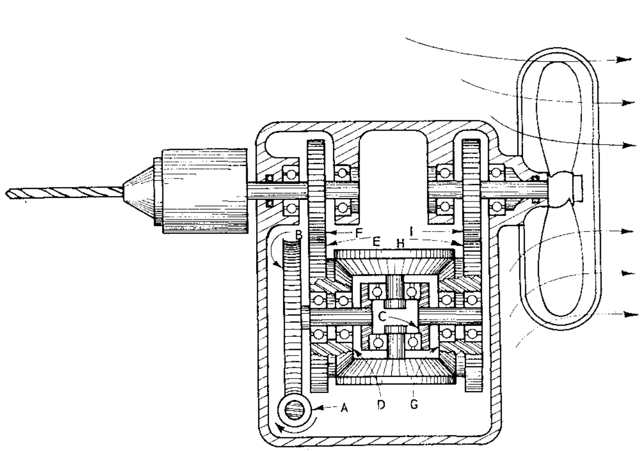

Fig. 8 Air-powered underwater drill.

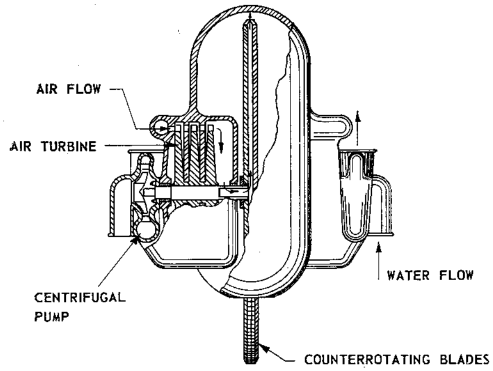

Fig. 9 Air-powered underwater saw.

mounted on the drill spindle. The right-hand bevel gear G of the differential, through the attached spur gear H, drives spur gear I which is mounted on a propeller shaft.

With this arrangement the drill will turn in one direction and the propeller will turn in the opposite direction. The propeller serves two functions: the torque of the propeller opposes that imposed on the drill when penetrating material, and the thrust of the propeller delivers an axial force which drives the drill into the work.

The differential gear assembly is used rather than a set of bevel gears to provide a torque balance under a variety of drilling conditions. For very heavy work the torque reaction on the drill spindle will slow it down. This will cause the right-hand element of the differential to run at higher speed, resulting in a greater torque and thrust being delivered by the propeller. Similarly if the work is light, the drill will turn at high speed and the propeller at low speed. Over a wide range of conditions the torques will be balanced with no reaction torque being applied to the operator. These same principles can be applied to the design of power tools for driving bolts and nuts or for power screwdrivers.

Another underwater power tool that will have some application is a saw. Sawing is also an operation in which either thrust or torque reactions on the operator must be balanced out. Figure 9 shows one concept of such a tool.

A pair of circular saw blades are driven by counter-rotating air turbines which in turn are driven from the compressed air supply. These turbines exhaust into the space between the blades which provides an air film to keep them separated and forces cuttings to be discharged radially. The opposite rotation of the blades will provide a torque balance so that there will be no torque reaction on the operator.

In sawing it is not necessary that a large force be exerted to drive the blades into the work. However, some force is needed in the direction of saw travel and downward into the work. In the unit shown, this force is provided by a pair of centrifugal pump assemblies mounted on the outer ends of the turbine shafts. Suction is taken from the lower forward part of the saw and the pumps discharge out of the upper after end of the saw, thus producing the desired force.

The underwater power tools that have been illustrated are not intended to be final designs of equipment. Rather they are an attempt to show the principles that can be employed to provide the force and torque balances necessary in underwater work. In general it is desirable that the unusual characteristics of the underwater environment be employed to improve the efficiency of the tool rather than detract from it.

All tools must be built of corrosion-resisting materials. The compressed-air medium should be utilized to apply internal pressure to all working parts of the tool to prevent the influx of salt water. Insofar as possible the tools should be designed with enough internal space so that they are neutrally buoyant. And of course there should be built in enough safety features so that the danger to the underwater operator is at a minimum.

Pneumatic tools for use on land are generally designed for a relatively small pressure drop. They are supplied with air at pressures ranging from 60- to 125-psi gage and exhaust at atmospheric pressure. In underwater work the supply pressure may range from 2500 psig to around 400 psig with exhaust at ambient pressures ranging from atmospheric to 150 psig. This imposes a rather difficult requirement in the design of underwater tools.

It would be wasteful of the available stored power to drop the tank pressure to a lower tool supply pressure through a reducing valve. The energy involved in the reduction goes into chilling the surrounding water. It may be possible, however, to obtain a more reasonable tool supply pressure and still obtain useful work from the initial pressure drop.

In the deeper underwater environment there is always a need for light. Adequate lighting is a particular requirement in the immediate work area. In fact it would be desirable to have a light mounted on each tool or at least on the air tank supplying compressed air for that tool.

Electric power for these lights could be supplied by small air-motor-generator sets which could be designed to operate on a pressure drop from tank pressure down to around 400 psig. In this way the energy of air expansion down to the tool supply pressure could be recaptured and put to doing useful work.

In this paper I have attempted to outline some of the problems and potential solutions involved in enabling man to perform underwater work with some degree of efficiency. The auxiliary power supplied to him and the tools that he uses will necessarily differ considerably from those employed in surface operations. It is essential that careful and imaginative designs be developed to avoid the deleterious effects of the underwater environment and to make the natural characteristics of this environment work for man rather than against him.